HABITAT MAPPING FOR CONSERVATION PLANNING IN BAA ATOLL, REPUBLIC OF MALDIVES

BY

SERGE ANDRÉFOUËT,[1] YOSSUF RILWAN,[2] AND MÉLANIE A. HAMEL[1]

ABSTRACT

In order to propose spatially-explicit conservation strategies driven by biodiversity for Baa Atoll, habitat maps were created from LANDSAT and Quickbird satellite images. The LANDSAT derived habitat map described the atoll geomorphology following the Millennium Coral Reef Mapping Project typology, which is made of 5 different hierarchical levels. The Quickbird derived high spatial resolution habitat map is a map of both geomorphological and benthic hierarchical information. Benthic information comes from 24 field stations surveyed in May-June 2009 for this project, and from an independent survey that quantified forereef coral cover and dominant growth forms for all the reefs found in Baa Atoll in June 2008. The Quickbird derived habitat map is created to take advantage of this extensive data set, which minimizes mapping errors on forereefs. Other reef zones were also mapped by considering the hierarchical level (geomorphology and benthic if possible) that minimized photo-interpretation uncertainty. Both habitat maps were processed to display habitat richness for all virtual management units found along a regular grid (1 km^2-cell). The differences due to different spatial and thematic resolution are discussed.

INTRODUCTION

Habitat mapping in coral reef environments is now a routine activity supporting fishery management, biodiversity inventories, niche modeling, and conservation planning (Andréfouët 2008; Purkis et al., 2008; Hamel and Andréfouët 2010; Dalleau et al., 2010). Remote sensing data routinely offers the necessary synoptic spatial background, at very high spatial resolution, typically within a range of one to five meters (Andréfouët 2010). The limits of remote sensing data are now well established, the methods well documented, and very high spatial resolution sensors can achieved a high accuracy. However, there are always site-specific and application-specific aspects that may call for an adaptation of the methods to apply, an adaptation in the design of the habitat typology to map, and an adaptation of the accuracy assessment protocol (Gilbert et al., 2006).

[1] Institut de Recherche Pour le Développement, IRD Nouméa, UMR 227 COREUS, BP A5, 98800 Nouméa cedex, New-Caledonia
[2] Marine Research Center, H. White waves, Moonlight Higun, Malé – 20025, Maldives

In coordination with the Atoll Ecosystem Conservation (AEC) project of Baa Atoll and the Marine Research Center of Maldives, we used habitat maps derived from remote sensing to stratify the biodiversity sampling (results reported in this volume by Bigot and Hamir, Andréfouët et al.; Payri and Mattio; Gravier-Bonnet and Bourmaud; Chabanet et al.) and to create spatially-explicit scenarios for conservation of habitats and biodiversity (Hamel and Andréfouët, this issue).

Here, we report on the specific aspects of the habitat mapping component of the Baa Atoll conservation project. We present the habitat survey and the resulting typology, the images used for the mapping, the specific principles used to map Baa habitats, and the mapped products.

MATERIAL AND METHODS

Field Data and Habitat Typology

Habitats were described in June 2009 for 24 sites across Baa Atoll (Fig. 1). The 24 sites included lagoon and oceanic sites (Fig. 1). Each site offered an opportunity to document and to add to the typology a number of habitats found between 30 meters and the surface. A habitat typically extends over few tens of meters, but can be restricted to small meter-scale patches, or being located at narrow edges, escarpments and fronts.

As traditionally used now in a remote sensing context, habitats were described using a hierarchy of geomorphological, benthic cover, architectural (coral growth forms and seascape rugosity) and taxonomic information for the dominant habitat-structuring species. Each habitat was described using a medium-scale approach (Clua et al., 2006), and by taking wide-angle and medium-angle photography for archiving. Each different combination of variables found in the field provided a new habitat for the typology.

To complement the description of the habitats found in 23 sites, we also used the results from Le Berre et al. (2009) acquired for the AEC project. This extensive work provided coral cover and dominant growth forms around each Baa Atoll reef, thus covering the entire atoll with at least one observation for each section of reef, across the entire range of degrees of exposure. Le Berre et al. (2009) data were acquired in June 2008 by towing a snorkeler at the surface and in shallow waters (<10 meters deep) close to the reef. Photo transects (five pictures per transect) were conducted at the beginning and end of each of the 505 tows. The average tow length was 1.25 km. Photo transects were processed with the Coral Point Count with Excel extension (CPCe) software. Quantitative estimates of cover were obtained using 25 points per photo. Growth forms categories included: massive, tabular, branching, foliose, encrusting, digitate and submassive.

Remote Sensing and Map Data

To help planning the survey, and for subsequent conservation planning analyses, we used first a map from the Millennium Coral Reef Mapping Project (Andréfouët et al.,

2006). The Millennium map of Baa was obtained from two Landsat images at 30 meter-resolution, from path-row 145-56 (acquired in 2000) and 145-57 (acquired in 2001). The classes mapped are geomorphological. They describe the main reef types and their geomorphological units, following a globally-valid protocol and classification scheme. Fifteen classes were needed to map Baa Atoll (Fig. 2).

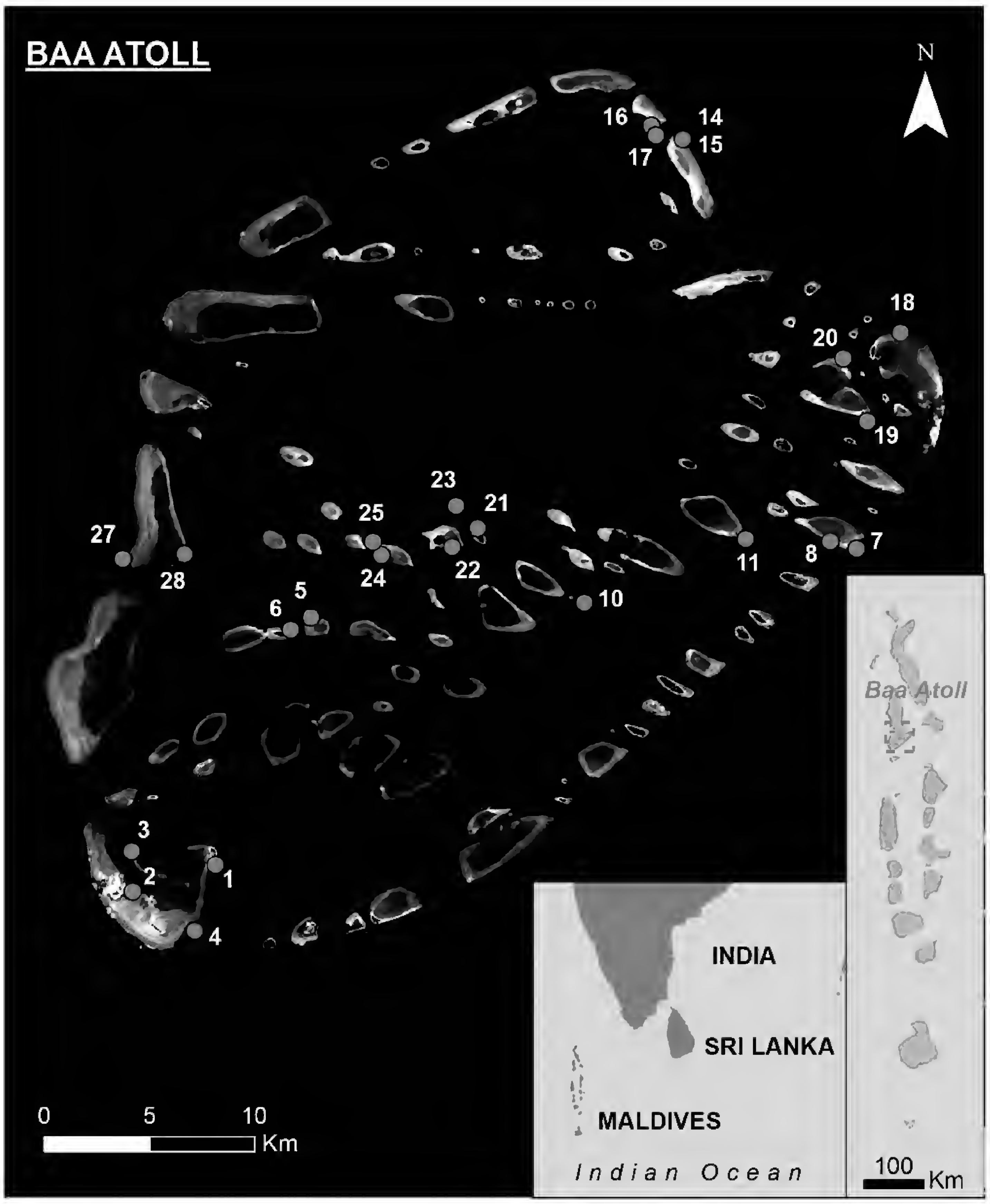

Figure 1. Map of Baa Atoll and position of the 24 habitat sampling sites visited in June 2009.

In 2010, the Department of Planning of the government of Maldives and the Marine Research Center provided a complete coverage of recent Quickbird images at 2.4 meter resolution. To cover the atoll entirely, different overlapping images acquired at different dates were needed. This resulted in a mosaic of heterogeneous quality due to different sea surface roughness and cloud covers. Each individual reef was thus processed independently, by taking advantage of the best coverage available. For the mapping, images were resampled at 5 meter resolution. No atmospheric correction nor water column correction was performed since most of the mapping was done by manual digitization, following the principles described in Andréfouët (2008). Sea surface correction was applied when needed, using the method by Hochberg et al. (2003).

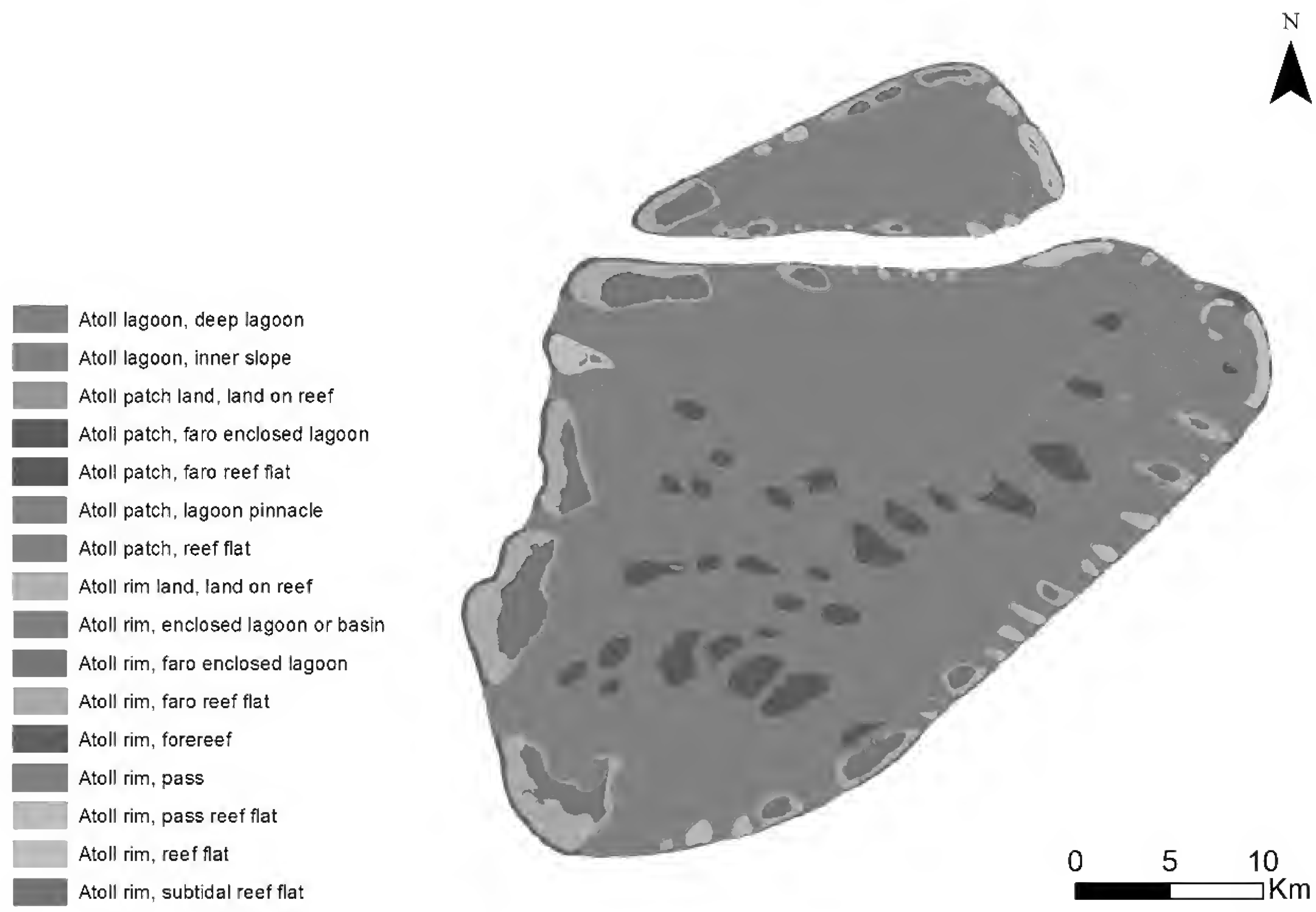

Figure 2. Millennium geomorphological map of Baa Atoll.

Principles for Mapping Baa Atoll for a Conservation Planning Application

The habitat mapping of Baa Atoll was conducted using the following principles: First, the data from Le Berre et al. (2009) covered the entire atoll, providing coral cover and dominant growth forms for each of the polygons corresponding to the upper forereefs of each mapped reef. Thus, we virtually eliminated omission errors (i.e., all habitats are represented at least once, where they were seen), but not necessarily commission errors for forereef habitats. This was acceptable given the final objective of the mapping, which is to use diversity of habitats for conservation planning (1km^2 management units). With this criterion, it was important to include in the mapping all the habitats observed at least

once in the field, even if the spatial generalization was uncertain. Since Le Berre et al. (2009) provided a very dense array of observations, we could be certain that forereef habitat diversity would be correctly represented in the habitat map using this process.

Second, in other areas where ground-truthing was limited (in particular on reef flats), we limited the mapping at the hierarchical level of the habitat typology where uncertainties were minimized. Thus, if field data and images could not provide unambiguous clues on benthic coverage and architecture, we limited the habitat description to a detailed geomorphological description, higher in the hierarchy, and with a greater degree of certainty. Typically, branching communities on sandy bottoms and seagrasses coud be discriminated, but this was not necessarily the case for all the different coral assemblages found on hard-bottoms. Deep mesophotic lagoon areas, which were not sampled and described by Le Berre et al. (2009) remained mapped as “Deep lagoon”.

Using the two principles above led to a low error map. However, different polygons may be labelled at different levels in the hierarchical habitat typology. Each habitat, either fully resolved or partially resolved throughout the hierarchy, was assigned a consistent weighting when deriving maps of habitat richness. This is a limitation that we acknowledge, as a generic “faro reef flat” will likely include more benthic and architectural variation than a “seagrass bed dominated by *Thalassia hemprichi, on faro reef flat*”

RESULTS

Qualitative General Field Observations

All the observations on the 24 sites confirmed the observations reported by Le Berre et al. (2009). The Figure 3 illustrates some of the habitats found in Baa.

Between 0-25 meters depth, the benthic and architectural complexity was low compared to other high island sites but comparable to atolls elsewhere in the world. The absence of fleshy algae-dominated habitats was noteworthy, as were limited seagrass habitats and the high occurrences of habitats dominated by coralline encrusting algae over remnants of coral formation, probably killed by the 1998 bleaching events. Eroded formations and breakages were frequent in lagoonal reefs, resulting in accumulation of loose substrate, or or substrate undergoing a process of cementation. Outer reef flats (crests) of the eastern outer rim (western outer rim reef flats were not visited) were mostly covered by small boulders exhibiting sharp transition towards pavement or sand habitats. Coral dominated habitats occurred on central lagoonal patch reefs (dominated by *Acropora* spp formations), and north-east oceanic slopes (*Porites* spp dominated formations). Mixed benthic assemblages were also found on the lower part of the lagoonal forereefs, and lagoonal reef flat tops. Sand and sediment plains dominated the 25-50 meters zone. In passes and pinnacles, high current zones, medium-high topography, overhangs, and small caves combined to provide habitats rich in fauna that frequently correspond to commercial dive sites. Low relief spur and grooves systems were dominated by pavement on the southern and western sides of the atoll. They appeared colonized by coral colonies of homogeneous sizes (communities of *Acropora* or *Pocillopora*), suggesting a recruitment episode 5-6 years ago.

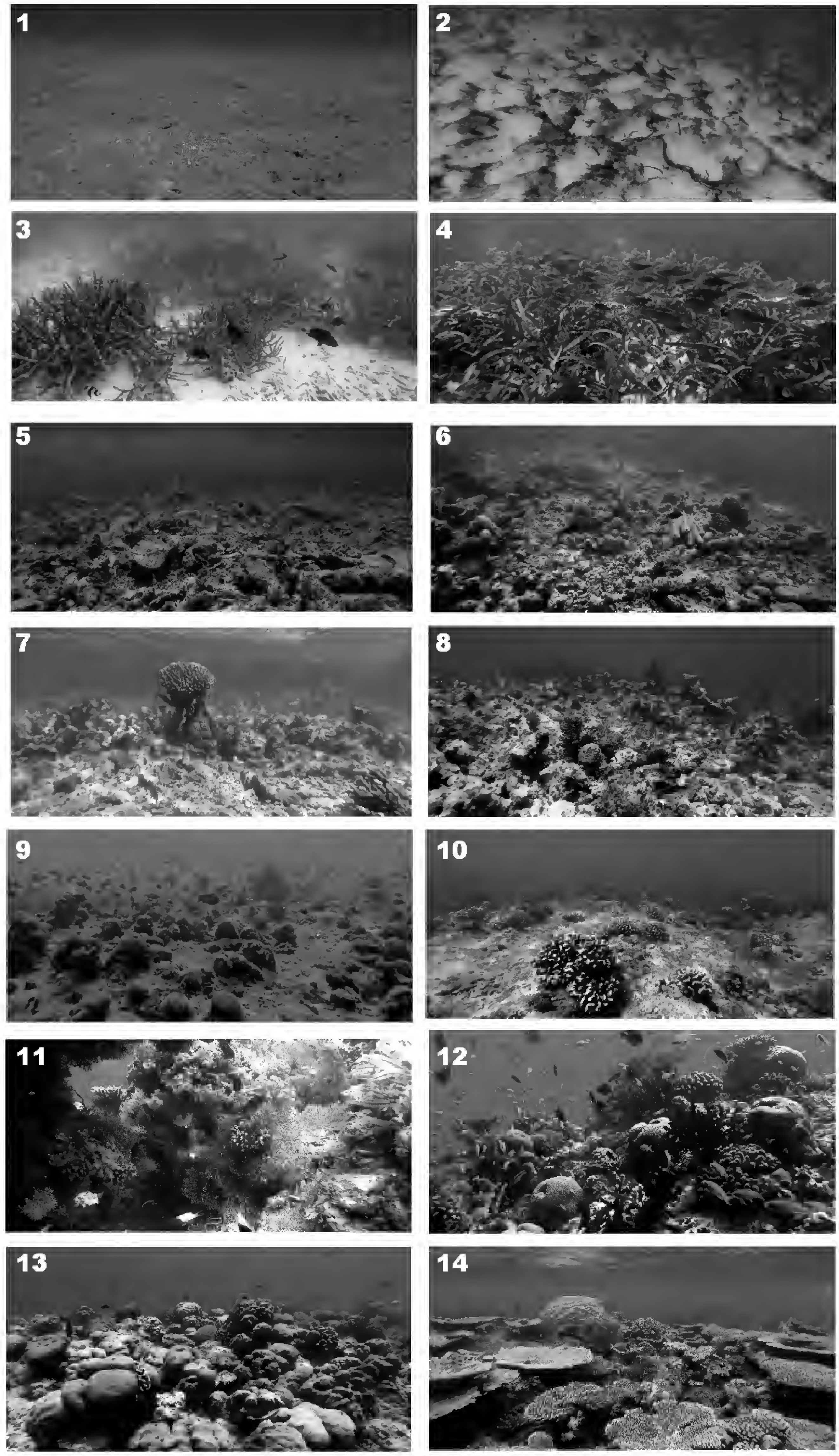

Figure 3. Examples of reef habitat found in Baa Atoll. From soft-bottom habitats (1-4) to boulder (5) to rubbles (6) to eroded coral substrates (7-8) to pavement with scattered corals of homogeneous sizes (9-10) to rugose and high current areas pinnacles and passes (11-12) to live massive or tabular coral dominated communities on reef tops (13-14).

Habitat Typology

Details of the habitat hierarchical typology are provided in Table 1 (geomorphology) and Table 2 (benthic cover and architecture). This typology was used to map habitats using the Quickbird images.

The geomorphology description (Table 1) is a three-level hierarchy, in agreement with the Millennium typology, but also with a few additional classes. The atoll is made of three Level 1 main structures (rim, patch reefs, and the lagoon) which themselves can be decomposed in a variety of geomorphological units at Level 2. Level 2 units can themselves be decomposed further in some cases. A label "*with constructions*" means that the image revealed numerous small coral constructions that were not individually mapped. They are aggregated and labeled as "*with constructions*". There were a total of 41 combinations, thus 41 classes. The islands described in detail by Kench (this issue) correspond to codes 10 and 27, respectively sitting on the rim and on central patch reefs.

Table 1. Geomorphological descriptors of the habitat typology. The column ID-G refer to the 1st and 2nd digit of the codes assigned to mapped polygons (see Fig. 4).

GEOMORPHOLOGY

ID-G	Geomorphology_L1	Code-GL1	Geomorphology_L2	Code_GL2	Geomorphology_L3	Code_GL3
10	Rim	1	Land	1	NA	0
11	Rim	1	Faro Enclosed Lagoon	2	Lagoon	1
12	Rim	1	Faro Enclosed Lagoon	2	Patch reef	2
47	Rim	1	Faro Enclosed Lagoon	2	Lagoon W/constructions	2
13	Rim	1	Faro Reef Flat	3	NA	0
14	Rim	1	Reef Flat	4	NA	0
15	Rim	1	Outer Forereef	5	NA	0
16	Rim	1	Inner Forereef	6	NA	0
17	Rim	1	Terrace	7	NA	0
18	Rim	1	Terrace w/constructions	8	NA	0
19	Rim	1	Deep Terrace	9	NA	0
20	Rim	1	Deep Terrace w/constructions	10	NA	0
21	Rim	1	Pass	11	NA	0
22	Rim	1	Pass Reef Flat	12	NA	0
23	Rim	1	Channel	13	NA	0
24	Rim	1	Subtidal Reef Flat	14	NA	0
25	Rim	1	Inner Reef Flat	15	NA	0
26	Rim	1	Pinacle	16	NA	0
49	Rim	1	Drowned reef	18	N/A	0
27	Patch Reef	2	Land	1	NA	0
28	Patch Reef	2	Faro Enclosed Lagoon	2	Lagoon	1
29	Patch Reef	2	Faro Enclosed Lagoon	2	Patch reef	2
48	Patch Reef	2	Faro Enclosed Lagoon	2	Lagoon W/constructions	2
30	Patch Reef	2	Faro Reef Flat	3	NA	0
31	Patch Reef	2	Reef Flat	4	NA	0
32	Patch Reef	2	Outer Forereef	5	NA	0
33	Patch Reef	2	Inner Forereef	6	NA	0
34	Patch Reef	2	Terrace	7	NA	0
35	Patch Reef	2	Terrace w/constructions	8	NA	0
36	Patch Reef	2	Deep Terrace	9	NA	0
37	Patch Reef	2	Deep Terrace w/constructions	10	NA	0
38	Patch Reef	2	Channel	13	NA	0
39	Patch Reef	2	Subtidal Reef Flat	14	NA	0
40	Patch Reef	2	Inner Reef Flat	15	NA	0
41	Patch Reef	2	Pinacle	16	NA	0
43	Lagoon	3	Terrace	7	NA	0
44	Lagoon	3	Terrace w/constructions	8	NA	0
45	Lagoon	3	Deep Terrace	9	NA	0
46	Lagoon	3	Deep Terrace w/constructions	10	NA	0
42	Lagoon	3	Deep Lagoon	17	NA	0
50	Lagoon	3	Pass	19	NA	0

Table 2. Benthic and architectural descriptors of the habitat typology. The column ID-B refer to the 3rd and 4th digit of the codes assigned to the mapped polygons (see Fig. 4).

Benthic cover and architecture

ID-B	Live Coral Cover (%)	Code_LCC	Benthic Community/Growth Form	Code_BCGF
50	0 - 5	1	Massive > 50%	1
51	0 - 5	1	Tabular > 50%	2
52	0 - 5	1	Encrusting > 50%	3
53	0 - 5	1	Digitate > 50%	4
54	0 - 5	1	Mix	5
55	0 - 5	1	Branching > 50%	6
56	0 - 5	1	Sub-Massive > 50%	7
57	0 - 5	1	Seagrass	8
58	5 - 10	2	Massive > 50%	1
59	5 - 10	2	Tabular > 50%	2
60	5 - 10	2	Encrusting > 50%	3
61	5 - 10	2	Digitate > 50%	4
62	5 - 10	2	Mix	5
63	5 - 10	2	Branching > 50%	6
64	5 - 10	2	Sub-Massive > 50%	7
65	10 - 15	3	Massive > 50%	1
66	10 - 15	3	Tabular > 50%	2
67	10 - 15	3	Encrusting > 50%	3
68	10 - 15	3	Digitate > 50%	4
69	10 - 15	3	Mix	5
70	10 - 15	3	Branching > 50%	6
71	10 - 15	3	Sub-Massive > 50%	7
72	15 - 25	4	Massive > 50%	1
73	15 - 25	4	Tabular > 50%	2
74	15 - 25	4	Encrusting > 50%	3
75	15 - 25	4	Digitate > 50%	4
76	15 - 25	4	Mix	5
77	15 - 25	4	Branching > 50%	6
78	15 - 25	4	Sub-Massive > 50%	7
79	25 - 40	5	Massive > 50%	1
80	25 - 40	5	Tabular > 50%	2
81	25 - 40	5	Encrusting > 50%	3
82	25 - 40	5	Digitate > 50%	4
83	25 - 40	5	Mix	5
84	25 - 40	5	Branching > 50%	6
85	25 - 40	5	Sub-Massive > 50%	7
86	> 40	6	Massive > 50%	1
87	> 40	6	Tabular > 50%	2
88	> 40	6	Encrusting > 50%	3
89	> 40	6	Digitate > 50%	4
90	> 40	6	Mix	5
91	> 40	6	Branching > 50%	6
92	> 40	6	Sub-Massive > 50%	7

Benthic descriptors used for the mapping included live coral cover (percentage) and dominant growth forms used principally to detail coral communities on both hard and soft substrates (Table 2 below). Distinctions between hard and soft substrates are not themselves part of the benthic description in contrast with usual practice for mapping. Indeed, since they appear implicitly related to the geomorphological units (Table 1), we

avoided unnecessary redundancy by omitting explicitly this distinction at this benthic level. Combining the possible ranges of coral cover and growth forms generated a total of 43 benthic combinations, thus 43 classes. Seagrass beds characterized one benthic class with low coral cover.

Quickbird-derived Habitat Map

Habitat mapping was done by labeling each digitized polygon with a mandatory geomorphological code. When certain, a benthic code was concatenated to the geomorphology code. This was systematically done for foreeefs following the observations reported by Le Berre et al. (2009). The achieved Quickbird derived habitat product is shown Figure 4.

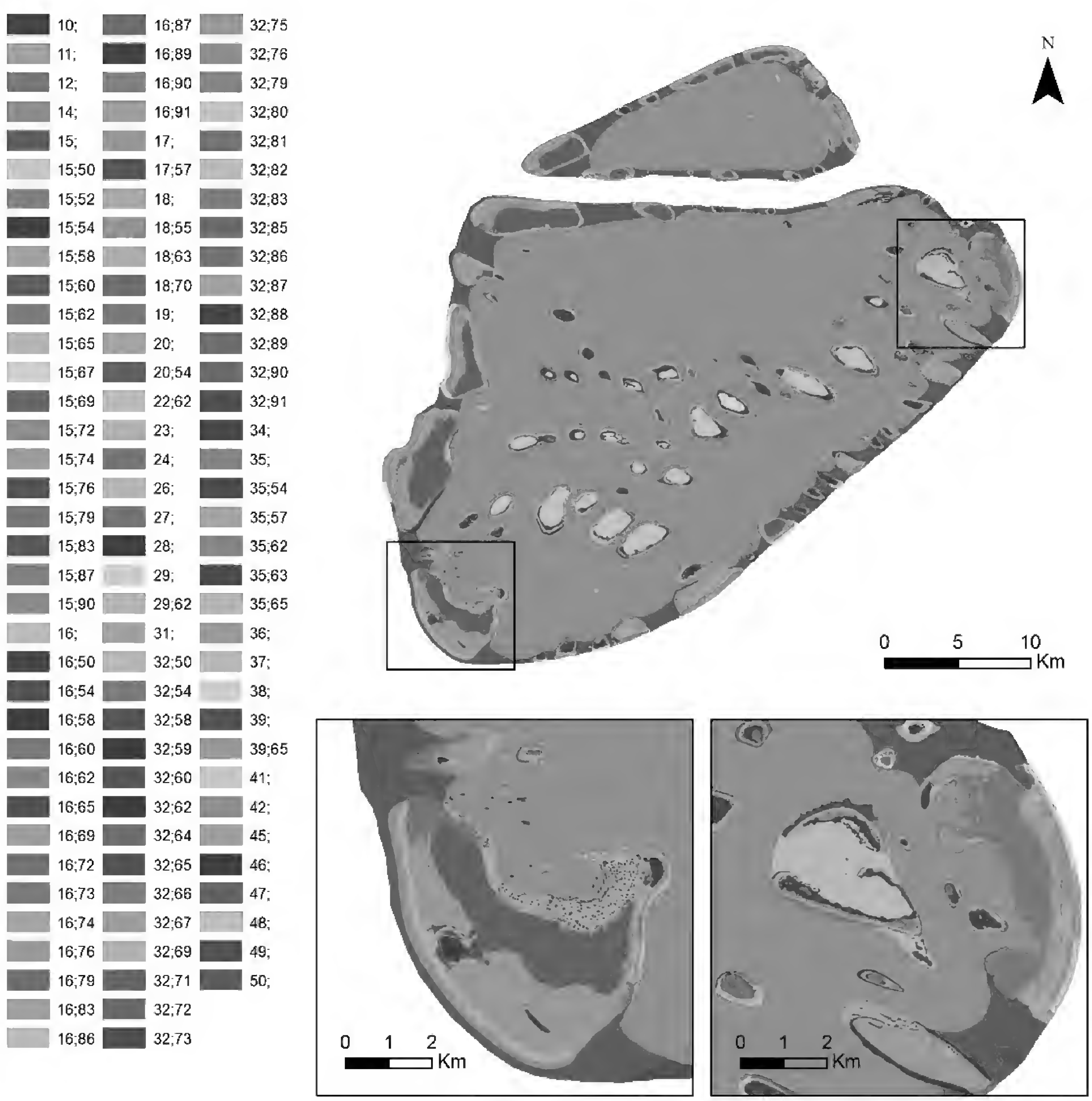

Figure 4. Illustration of the Quickbird-derived habitat maps. Each color corresponds to a different habitat. Two enlargements are shown for structurally complex areas, with numerous patch reefs. The two first digits of the codes refer to geomorphology (cf. Table 1, ID-G). With 4-digit codes, the two last digits refer to benthic description (cf. Table 2, ID-B)

Considering the full hierarchy, the complexity of the product reaches 106 habitat classes (Fig. 4). This is a very high number of classes, but in agreement with the level of detail that can be achieved following Andréfouët (2008)'s user oriented scheme. The input provided by Le Berre et al. (2009) data significantly increased the complexity, compared to what could be typically done without similar amount of field data (e.g., 56 classes in Wallis Island, a high island with fringing, patch and barrier reefs, Andréfouët, 2008).

The 106-class map highlights what is technically possible to achieve. However, managers and other users may not want to systematically consider such a high number of classes for their application. Obviously, few tens of classes represent a more manageable number, which may be more relevant for a given application (Gilbert et al. 2006). There is indeed a threshold in class numbers, above which plotting maps on screen and in print becomes confusing (Figure 4 illustrates the complexity of spatial patterns, but the color coding may not be optimal in print). The hierarchical attributes allow representing different information, geomorphologic (Fig. 5) and benthic (Fig. 6) depending on the needs, at a more traditional level of complexity.

DISCUSSION

Baa Atoll detailed habitat map was created following, for a large part, a standard mapping methodology (Andréfouët, 2008), but also following an unusual labeling procedure. Indeed, such labeling was only made possible with Le Berre et al. (2009) rapid survey dataset on coral cover and coral growth form. This dataset, exhaustive for the entire atoll, avoided the traditional accuracy assessment stage that should follow any mapping exercise to quantify the uncertainty and errors rates, and more importantly to provide confidence in the accuracy of the product. Here, confidence is brought by a map product constrained well enough by field data. Why? There are two reasons for that:

- First, for all forereef locations, there is at least one training ground-truth point for every polygon. This is luxury compared to most mapping projects. However, we acknowledge that variations may exist within each polygon, thus commission errors of unknown magnitude likely still exist.
- Second, the goal of the detailed Quickbird-derived map was to guide conservation choices. The goal was to identify areas of high habitat richness and define conservation area networks that would include occurrences of all habitats present in the atoll (Hamel and Andréfouët, this issue). Therefore, the required output was habitat richness, consistently estimated for each of the 1238 management unit (defined arbitrary as 1 km per 1 km cell by Hamel and Andréfouët, this issue). The mapping done here fulfilled this objective.

Below, we compare the different habitat richness products at 1 km resolution (Fig 7, 8 and 9). In Hamel and Andréfouët (this issue), we also compared the influence of the habitat map products for conservation scenario. Except Dalleau et al. (2010), to our knowledge, there are no other coral reef studies comparing the influence of maps with different thematic resolution for conservation planning. These comparisons help to define the relative benefits of using a detailed habitat map *vs* a coarse geomorphological map.

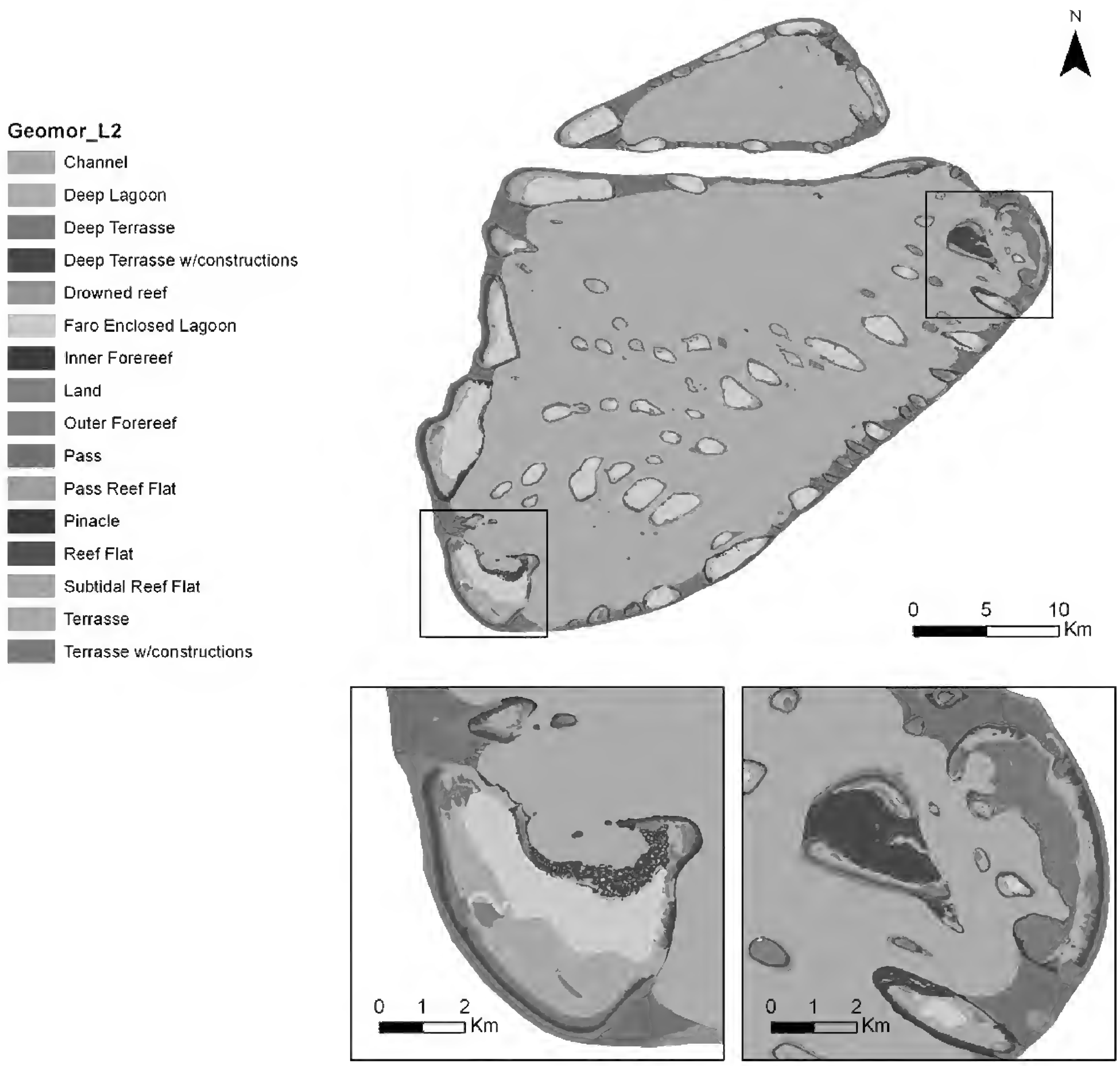

Figure 5. Illustration of the use of Quickbird-derived habitat maps. Each color corresponds to a different geomorphological class, at Level 2 (cf. Table 1, Geomorphology_L2). Two enlargements are shown for structurally complex areas, with numerous patch reefs.

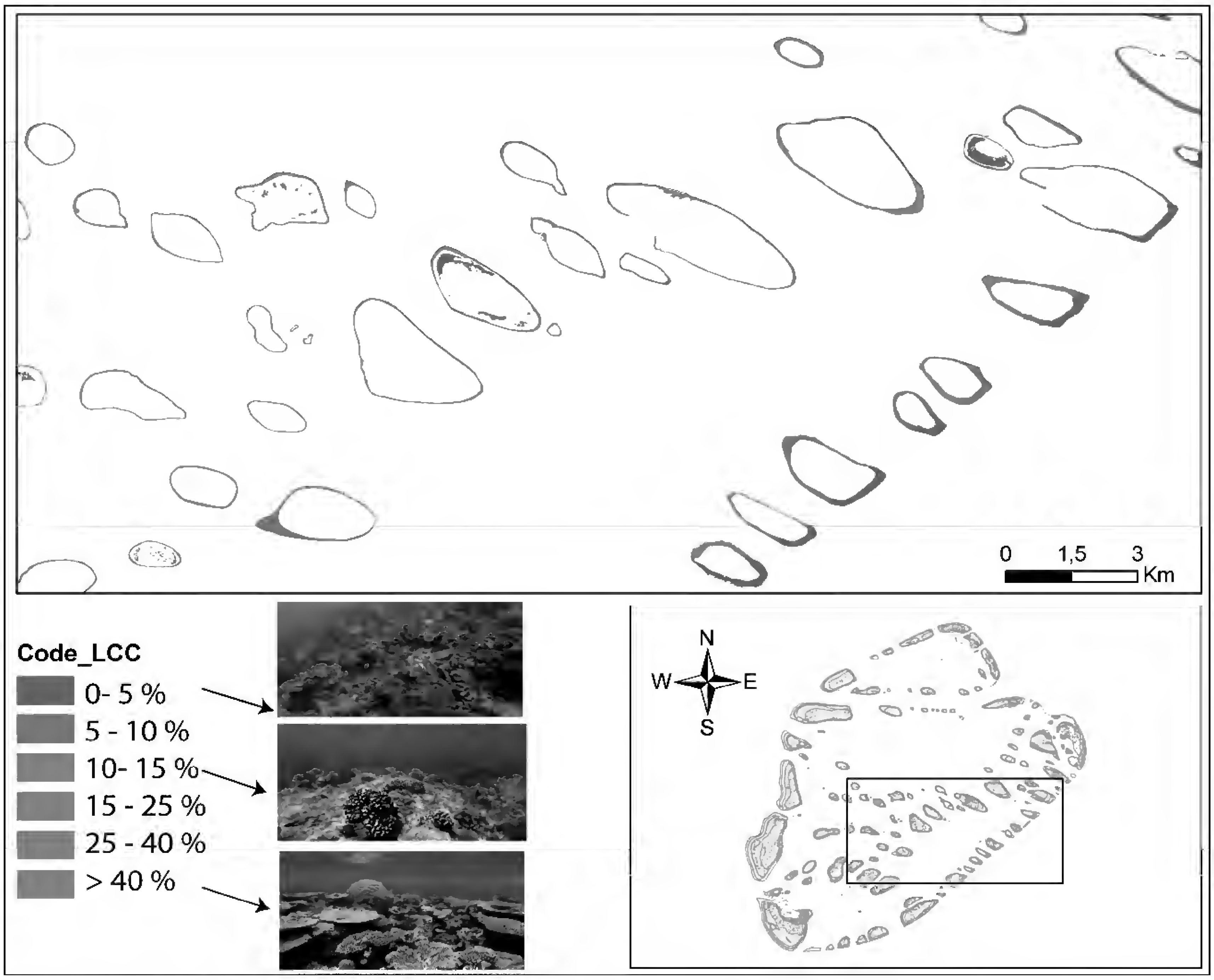

Figure 6. Illustration of the use of Quickbird-derived habitat maps. Each color corresponds to a different level of coral cover (cf. Table 2, Live Coral Cover %) Coral cover was assigned to forereefs, using Le Berre et al. (2009) data. Three examples of habitat illustrate coral cover levels. The map clearly shows the gradient from low coral cover on the oceanic forereefs to very high cover on the central patch reefs.

The relative patterns are consistent between the two products (Figs 7, 8 and 9), with higher diversity found along the atoll rim. However, in the Quickbird-derived habitat richness product, the central patch reefs are clearly more diverse than their LANDSAT counterpart. The figure 9 summarizes the differences. Also, given that the products are computed from respectively 15 and 106 classes, habitat rarity per grid cell is more frequent in the Quickbird product than in the LANDSAT one. Moreover, complementarity between sites is high. Thus, protected areas siting algorithms that use complementarity-rarity and complementarity-richness algorithms led to contrasted propositions of MPAs depending on which of the differing sensors were used (see Quickbird-derived MPA propositions in Hamel and Andréfouët, this issue). However, a caveat that we need to emphasize is that the computed richness as derived here is conservative. It is a minimum richness value. All polygons had the same weight in the richness analysis. It is possible that actual richness was higher on each mapped polygon than the value 1, due this time to intra-polygon omission errors (existing polygons could have been broken in more habitats if tow data from Le Berre et al. (2009) were at higher resolution). Furthermore, large polygons mapped only at geomorphological level likely include intrinsically more detailed habitats than polygons mapped with a geomorphology and benthos code.

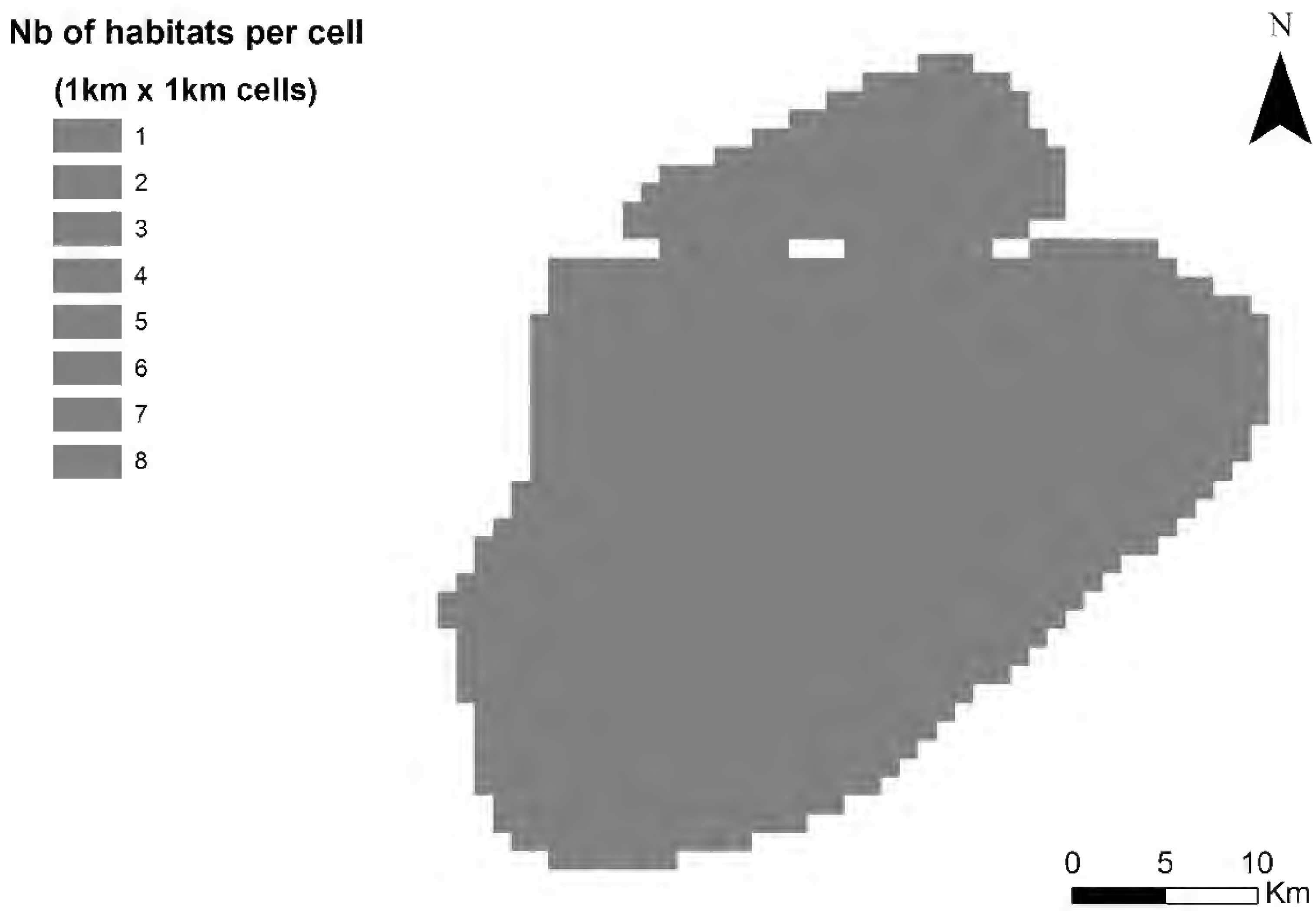

Figure 7: Geomorphological habitat richness (number of Millennium classes) for each cell of a 1 km grid overlaid on the Landsat derived habitat map.

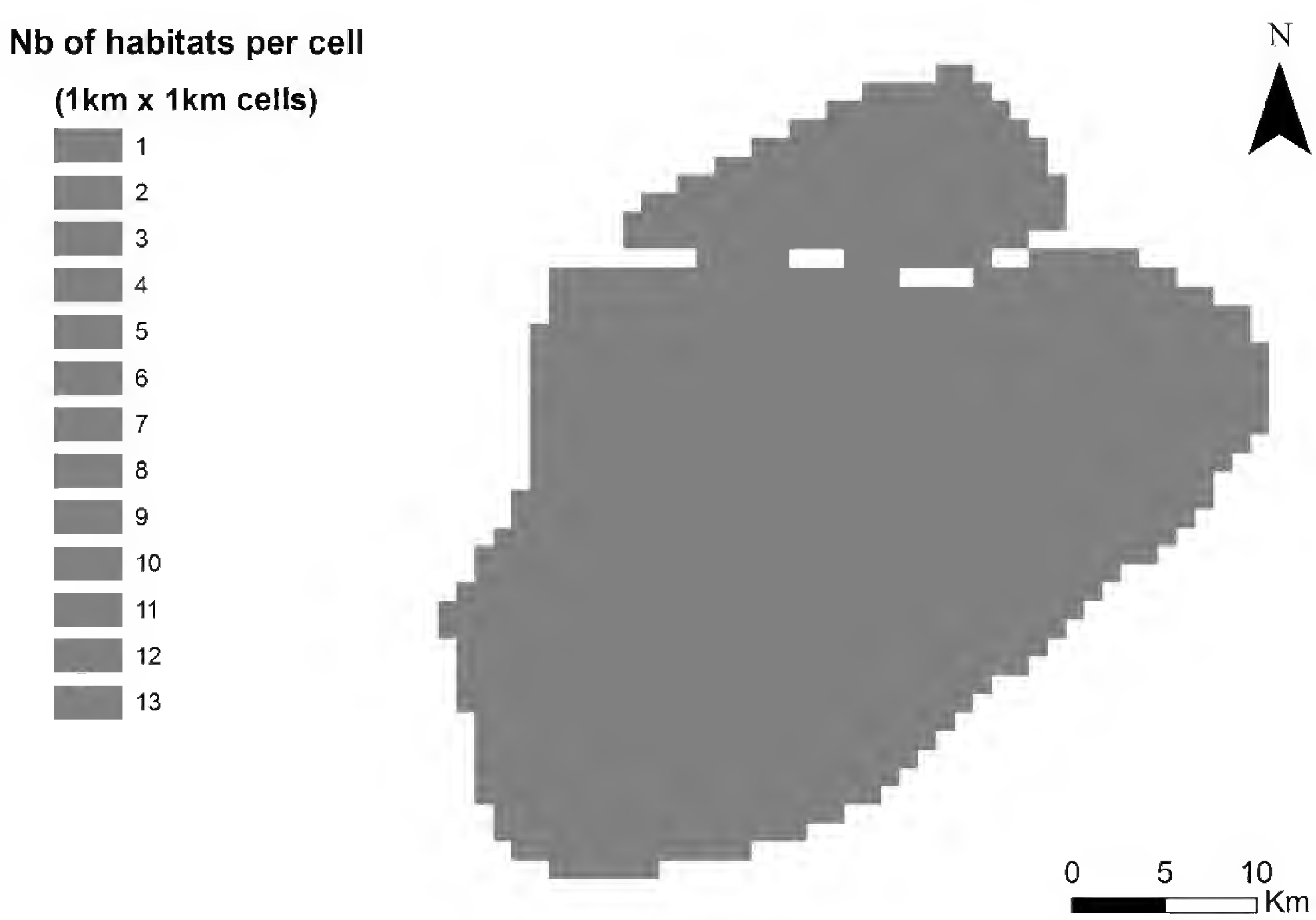

Figure 8: Habitat richness (number of habitats) for each cell of a 1 km grid overlaid on the Quickbird derived habitat map.

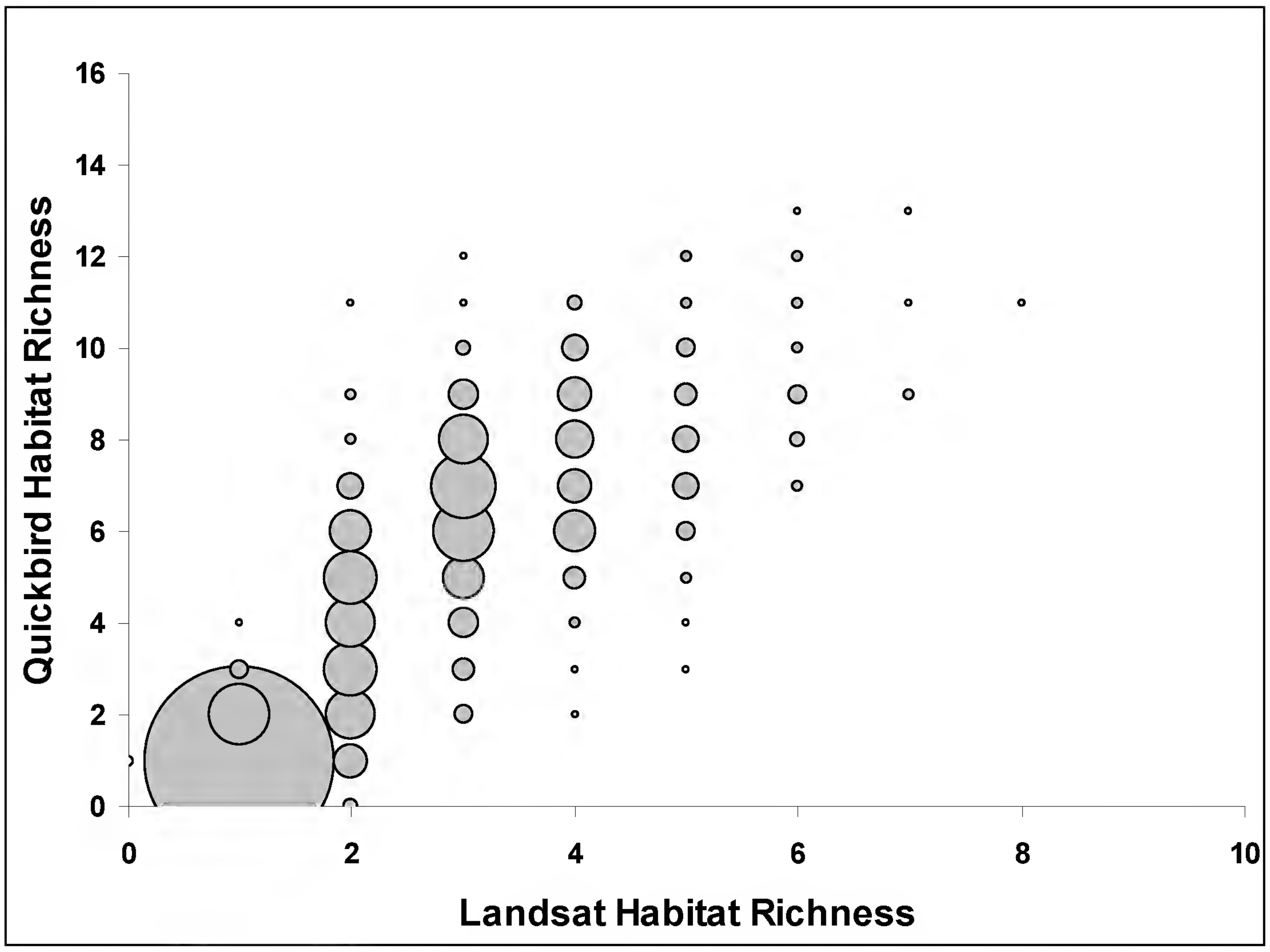

Figure 9: Comparison of Landsat-derived and Quickbird-derived habitat richness (number of habitats) for 1238 1-km² cells. The size of the bubbles is proportional to the number of cells with the given combination of richness. For instance, there are 501 cells with habitat richness equals to 1 for each sensor, in this case mostly found in the wide deep lagoon. Other bubbles represent between 1 and 64 co-occurrences.

CONCLUSION AND PERSPECTIVES

Geomorphology and benthic communities were mapped for the entire Baa Atoll using both LANDSAT and Quickbird satellite images. The mapping was conducted to serve conservation objectives (Hamel and Andréfouët, this issue).

To fill the gaps and continually improve the mapped product, further mapping work should now look in detail at polygons left mapped at coarse geomorphological level, especially those who are now included in protected areas or part of biodiversity and sea-level monitoring sites (Kench, this issue). The maps created here could also be immediately used to refine on-going monitoring programs with new sampling design based on an adaptive strategy, by combining spaceborne and field data (Scopélitis et al., 2010). There are still very few coral reef sites that benefit from detailed habitat maps at different thematic resolution, and on-going projects in Baa Atoll should take advantage of this in the future.s

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